A comprehensive classification of inland wetlands of Western Australia using the geomorphic-hydrologic approach

C A Semeniuk & V Semeniuk

V & C Semeniuk Research Group
21 Glenmere Road, Warwick, WA, 6024

Manuscript received December 2010; accepted June 2011

Abstract

An expanded site specific classification of wetlands using landform types and water regimes as fundamental and primary criteria is presented here. The subdivision of landform types host to wetlands now includes hills, cliffs, slopes, flats, vales, channels, and basins. Further to the initial subdivision of water regimes as permanent, seasonal and intermittent inundation, or seasonal waterlogging, is now added permanent waterlogging. Combining landform types and water regimes results in 22 primary categories of wetlands. Use of landform, water and vegetation descriptors further separate types of wetlands, and it is at this lower level that attributes such as scale (size), hydrochemistry, wetland plant communities, and origin, can be emphasised. Self-emergent wetlands are differentiated from *in situ* wetland accumulations associated with convex landforms and which conform to the underlying land surface. This classification may be used as the basis for a world register and/or mapping of wetlands from arid to humid climates, and the number of classes which cover the global diversity of wetlands at the primary level is relatively small.

Keywords: inland wetlands, wetland, classification, geomorphic-hydrologic, Western Australia

Introduction

Land, in a general sense, is that part of the Earth's surface that stands above mean sea level (Hettner 1928; Jackson 1997). Landforms and other features produced by natural processes, which comprise the Earth's surface, have characteristic and repetitive shapes. Major forms include mountains, plains and plateaux; minor forms include dunes, valleys, cliffs, hills, and slopes (von Engeln 1949; Fairbridge 1968; Jackson 1997). Wet landforms are also part of the Earth's land surface. The most obvious difference between wet landforms and all others is a predominance of water in the former (Warner 2004). Because of the richness and diversity of biological processes which take place in wetlands, the wide range of wet landforms have been variously defined, delineated, described, and categorised often from a consideration of what drives their productivity. In all cases, what drives productivity is the presence of water and the modification of its chemistry through geological/geomorphic, hydrological, hydrochemical, and biotic interactions. Definitions of wetlands have attempted to include the basic three wetland attributes of geologic/geomorphic, hydrologic and biotic features and processes. Boundaries of wetlands have been delineated with respect to their geological, hydrological, and biotic properties; and descriptions of wetlands have included geological, hydrological and biological attributes and values (Cowardin *et al* 1979; Ramsar 1996; Tiner 1999; Richardson & Vepraskas 2001). It is important that wetland classifications also incorporate these three attributes.

And herein begins the problem because two of these components are more stable (*viz.*, geologic/geomorphic and hydrologic) and find a longer term expression in nature than the third (*viz.*, biologic). Therefore, for the purposes of classification and mapping, the two components that are less dynamic and changeable, ideally, should be selected at the basic level, leaving the third important component of biology to be incorporated at higher levels. What this means is that attributes of land and water should constitute the primary level of classification while biological attributes should be added at subsequent levels to incorporate more detail

A classification of wetlands at the site-specific level, using the primary attributes of land and water, accompanied by second level descriptors, was devised for south-western Australian conditions (Semeniuk 1987; Semeniuk & Semeniuk 1995). This classification has been tested throughout different climatic and biogeographic regions, geological and physiographic provinces of Western Australia, Australia, and globally, and has been found to be applicable to a large range of wetlands. Since 1995, with a larger database and terrain testing, the original wetland classifications of Semeniuk (1987) and Semeniuk & Semeniuk (1995) were expanded to incorporate additional wetland types, hydrologic regimes, and to refine some terms. These changes are formalised in this paper.

The approach, underpinning the classification presented herein, rests on the premise that wetlands are essentially "wet landforms" and lend themselves to systematic classification initially on their landform and water characteristics. In this context, some ecosystems proposed to be wetlands by other authors, are excluded. Glacial ecosystems are excluded on the basis that their environmental driver is ice, not water. Underground ecosystems, such as caves, also are excluded on the basis that they do not occur *on* the land, but are subterranean.

Classification principles, existing wetland classification methods and criteria were reviewed by Semeniuk (1987) and Semeniuk & Semeniuk (1995, 1997, 2011). It is not intended to present further reviews in this paper, but the resulting changes to the existing geomorphic-hydrologic classification presented here are the outcome of this ongoing enquiry.

Landform refers to the structure or geometry of the land and not to the resulting combination of landform and accumulated wetland sedimentary fill. In Semeniuk & Semeniuk (1995), five landform types, which host wetlands, were identified: hills, slopes, flats, channels, and basins. As landforms are intergradational, two principles were established: 1. the complete landform should be classified and not compartmentalised into its smaller parts; and 2. in the situation where basins are interconnected, each basin is defined by its central depression even though the littoral zones of the adjacent basins may adjoin.

In Semeniuk & Semeniuk (1995), four categories of water regime or hydroperiod were identified: permanently inundated, seasonally inundated, intermittently inundated, and seasonally waterlogged. For the gradations between the categories, and hydroperiods, three principles were established: 1. hydrological condition should be the prevailing one, 2. hydrological condition should be based on the presence of water rather than its absence, and 3. an area of 10% of the wetland should be used as the cut off point between lake and sumpland during periods of surface water contraction (Semeniuk 1987). An example, in which the first principle is relevant, concerns the variable expressions of permanent inundation. All three of the following conditions are included in this category: 1. areas where water covers the land surface throughout the year in all years, 2. permanently flooded areas which seasonally or intermittently contract to a central pool (but > 10% of the basin area), exposing wetland margins, and 3. areas where water covers the land surface but which are intermittently exposed. The second principle directs classification of wetlands to the period when surface or subsurface water is present. The third principle enables the researcher or land manager to distinguish between a lake and a sumpland, using as a criterion, the percentage of wetland which is inundated.

Descriptors to further classify wetlands were used for both land and water. For land they were based on geometry, size, and vegetation cover and type (Semeniuk & Semeniuk 1995; Semeniuk *et al* 1990). For water they were primarily related to water salinity and its consistency.

The comprehensive geomorphic-hydrologic classification of wetlands

In the approach to wetland classification presented here, non-emergent wetlands are separated in the first instance from self-emergent wetlands. The latter, through vertical accretion of sedimentary materials or chemical and biogenic accumulations have mounded beyond the original land surface into a new convex wetland geomorphology (Fig. 1).

Non-emergent wetlands

Non-emergent wetlands are terrain conforming, and occur in any landscape where there is sufficient water to maintain them. The initial subdivision of landforms host to wetlands from the Swan Coastal Plain (Semeniuk 1987, and augmented in Semeniuk & Semeniuk 1995) has now been expanded to seven landforms, *viz.*, basins, channels, vales, flats, slopes, cliffs and hill-tops (Fig. 2). It should be noted that the individual landforms are not, at this level, subdivided into genetic types. For example, basins have not been subdivided into groups of glacial origin, those formed by fluvial action, shoreline processes, wind deflation or deposition, isostatic uplift or those of biotic origin. Nor have basins been distinguished on the basis of size, with larger basins separated from smaller or shallower ones. In this instance, the term "basin" is only employed to differentiate it from either a vertical or horizontal flat surface, a convex or sloping surface, or an open ended concave feature. As Coleman (2003) remarks "morphological features are usually obvious". They are also relatively slow to change, and hence lend themselves to classification.

As noted earlier, the requirement to identify an entire landform feature or geomorphic element excludes subdivision of landforms into smaller land components, such as 1. the littoral and the central parts of a wet basin, 2. the transition zone between upland and lowland, 3. the top and slope of a hill, 4. the area of basin behind a lunette that may occur within a wetland, 5. the pools and riffles of a channel, or 6. "fuzzy" non-prescriptive areas supporting a plant community.

Further to the initial subdivision of water regimes, *viz.*, permanently inundated, seasonally inundated, intermittently inundated, and seasonally waterlogged (Semeniuk 1987; Semeniuk & Semeniuk 1995), is now added a fifth – permanently waterlogged.

Water regimes are important to biological processes, population densities, community composition, and overall regeneration and ecological maintenance. The water regime is also important in determining the nature of wetland fills, the types of interactions between the geology, plants and water, and the resulting wetland hydrochemistry (Semeniuk 2007) which, in their turn, also influence biological and ecological functioning. Hydroperiod and the chemistry of waters will also determine the specific type of wetland that will develop (Warner 2004). Therefore, it is particularly important to distinguish between water that is permanently available, regardless of temperature, colour, depth, salinity, and dissolved oxygen, water that is available intermittently, but in a regular, cyclic, predictable, pattern, and water that is intermittently available in an unpredictable, opportunistic, longer term regime. Thus, three categories of cycle (or period) have been recognised – permanent, seasonal and intermittent. Seasonal and intermittent are distinguished on the important basis of a recurrence every year *versus* an occurrence of inundation every 5–20 years. It is also important to emphasise that the attribute selected for classification is the availability of water. The presence of ice in a wetland, and certainly permafrost, does not denote water availability. Wetlands, in which ice alternates with melt water, would fall into the category of a seasonal water regime.

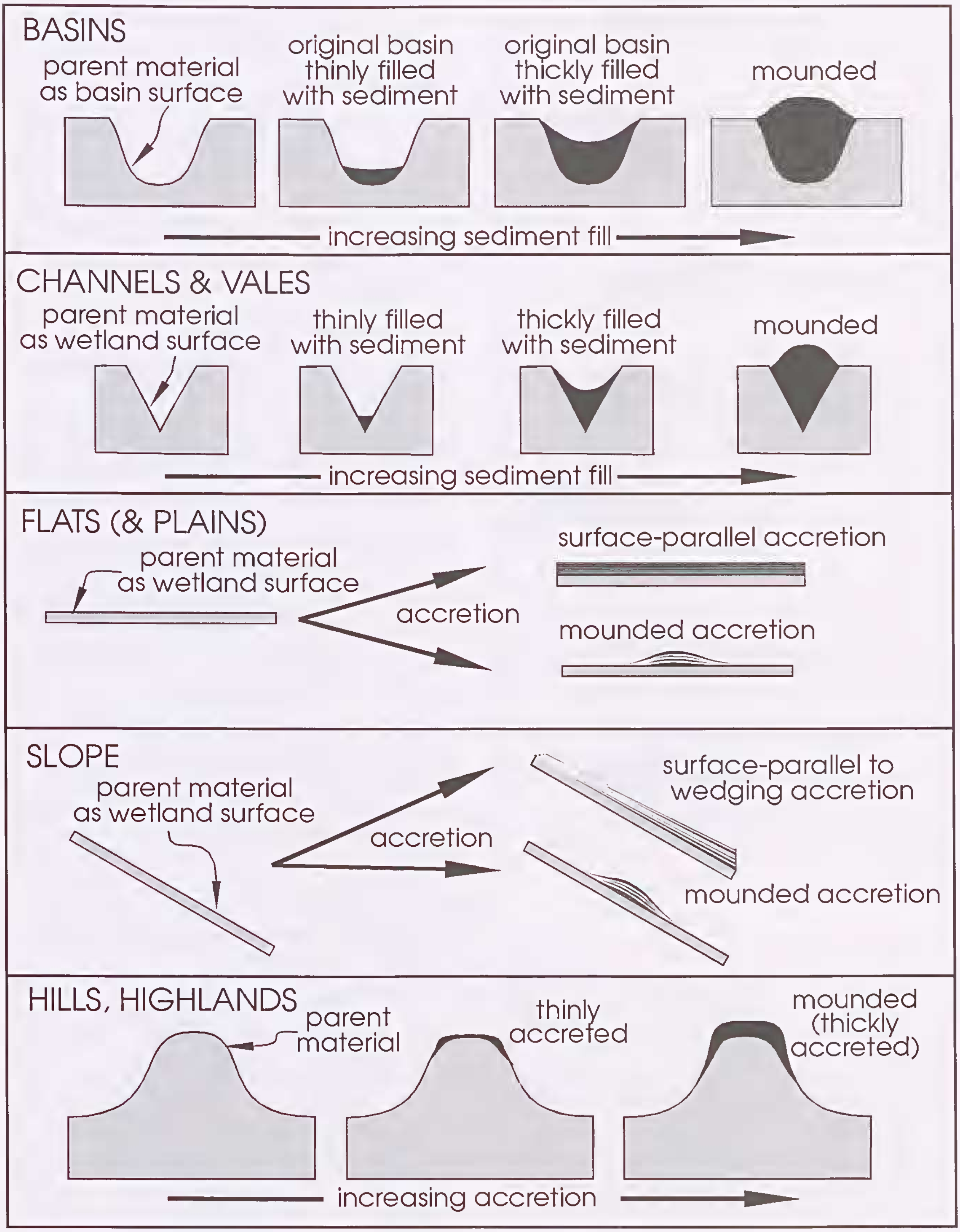

Figure 1. Stages in the accretion, filling or mounding of sediments, precipitates and biogenic deposits within and on wetlands.

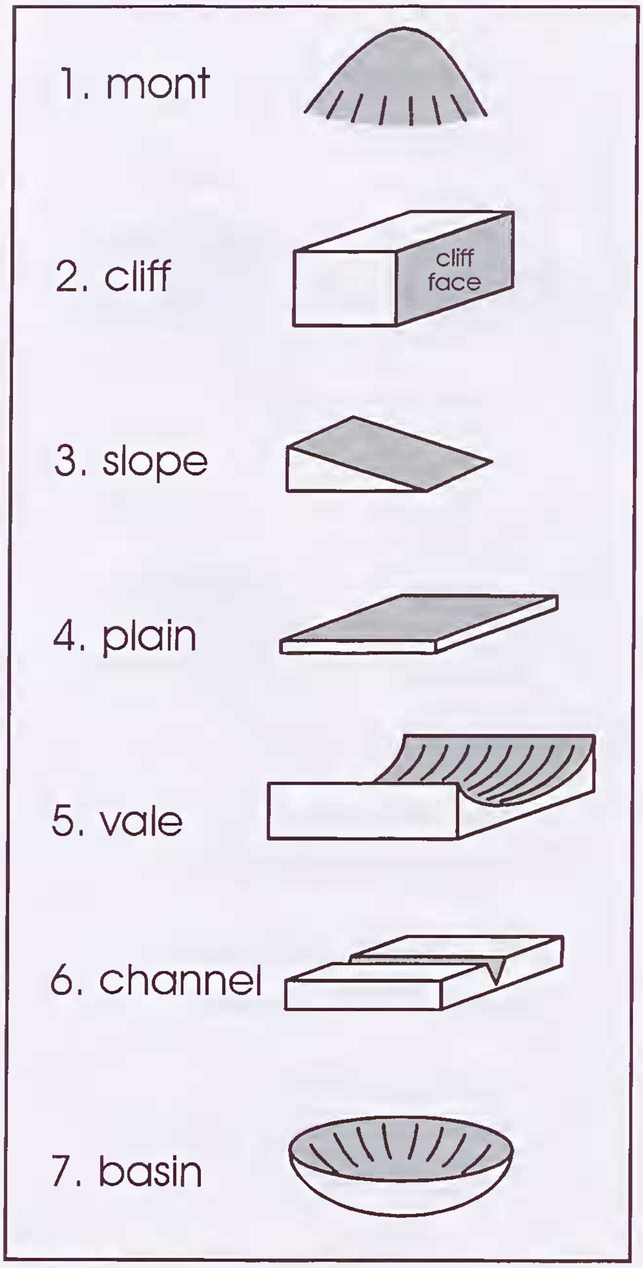

Figure 2. Seven landform types host to wetlands

Another aspect of the water regime relates to where the water resides. This distinction is made because biota have specific niches and because surface water and subsurface water are subject to different hydrological, chemical and ecological processes. Water that inundates the surface of the wetland may well also saturate the subsurface but this is not always the case. In many wetlands, in arid areas, or areas underlain by bedrock, water (as rainfall or as run-in) may be perched. Where surface water is present it is considered to be the source and driver of specific wetland functions and processes, wholly separate and different to the saturation of the subsurface sediments. These concepts are embedded in the terms inundation and waterlogging.

Definitions of terms for landscape and water regimes are provided in Tables 1 and 2.

Table 1

Types of wetland landforms

Landscape	Description/definition
basin	contained, closed depression in the landscape
channel	linear, though not necessarily straight open relatively narrow depression
vale	linear, open, relatively broad depression in the landscape, valley tract
flat (or plain)	flat or very slightly undulating terrain
slope	sloping surface
cliff	vertical or near vertical precipice; steep or overhanging face of rock
hill-top	convex upper surface of landscape

Table 2

Types of wetland water regimes

Water regime or hydroperiod	Description/definition
permanently inundated	water present above surface permanently, though its level may fluctuate
seasonally inundated	water present above surface on a seasonal basis
intermittently inundated	water present above surface intermittently, say, every 5–10 years
permanently waterlogged	water wetting or saturating the surface or near-surface permanently
seasonally waterlogged	water wetting or saturating the surface or near-surface seasonally

Vales and cliffs are the two new landform types used in the geomorphic-hydrologic classification in this paper. While the term valley describes narrow to broad u-shaped to v-shaped (straight, meandering, irregular) linear depressions, to gorges, that are often fluvial tracts of rivers, creeks, and wadis, and that range in size from tens of metres to tens of kilometres in width and several metres to a few hundred metres in relative depth, vales are small valleys. The cross-sectional form of a vale is generally smoothly u-shaped, showing no clear demarcation between the base and sides, and the development of wet flats and slopes, usually found in valleys, is minor, and discontinuous. Vales may or may not contain segments of small scale channels. Where a channel passes through a vale it is classified independently. Vales are commonly sites of saturation or waterlogging. Vales host to wetlands are underlain by soils or sediments diagenetically or pedogenically altered by waterlogging, and support wetland plant assemblages.

Cliffs are a product of rock outcrop weathering and erosion and have some affinity to slopes. There are several common locations where cliffs are present: at the coast, in the thalweg of a stream as it descends from plateau to plain, or from hanging valley to lower valley, on the edge of canyons, and in mountainous regions, where erosion is active. As coastal cliffs are a subset of coastal wetlands and this paper deals with inland wetlands, coastal cliffs are not described further here.

Cliffed sections of a stream channel, such as waterfalls along their tract, are not considered to be separate wetlands although they comprise separate habitats and components of the stream bed similar to internal pools, riffles, and point bars. Cliffs, as described here, refer to landforms associated with erosional processes of high land. They may occur in arid or humid environments. Wet cliffs are normally sites of permanent or seasonal waterlogging, due to seepage from, or between, rock strata. It is interesting to note that, similar to palusplains, the wetting of the surface may be patchy with saturated and unsaturated domains co-existing due to the conditions of water flow. As for other seasonally waterlogged landforms (palusplains, paluslopes, damplands), a thin veneer (film) of water trickling over the surface does not constitute inundation. The thin surface water is an expression of the process of seepage from a waterlogged porous, and/or granular medium. On cliffs, the hydrochemical and biological response to waterlogging is mineral precipitates or specific plants and biota colonizing the cliff surface.

The terms in Table 2, used to describe water regime or hydroperiod, correspond to recognizable states in hydrological and wetland ecological cycles, but may find various expressions in the short and longer term (Fig. 3). In the short term, the condition of 'permanent inundation' would be applied to wetlands with any depth of surface water, and in which there are considerable volume fluxes, whether seasonal or resulting from extraction. The term would be assigned to all of the following situations: constant surface water, surface water present throughout each year except in extreme drought, surface water with annually fluctuating levels, surface water ranging from 0.2 m or > 100 m. Wetlands with surface water levels which are declining or increasing gradually over a decade, but which remain inundated, would also fit into this category. However, in the longer term, for normally seasonally inundated wetlands, a single periodic decadal storm or cyclone event, resulting in a year long inundation would not shift the category of water regime to one of permanent inundation, as it is not the prevailing condition. A wetland which is dry more than 50% of the time would best be categorised as having a regime of intermittent inundation. Intermittent wetting implies that it is not part of an annual cycle or even a regular decadal cycle. Intermittent, as used here, incorporates the terms "intermittent", and "episodic" as used by Boulton & Brock (1999), and can be defined in their terms as a condition in which "annual inflow is less than the minimum annual loss in 90% of years". This means that the wetland would be "dry most of the time with rare and irregular wet phases that may persist for months" (Paijmans *et al* 1985; Boulton & Brock 1999). All unpredictable episodic rain events regardless of frequency are included in the term intermittent inundation. "Ephemeral" as defined by Boulton & Brock (1999) is not considered to be a wetland descriptor under the definition used here (Semeniuk 1987). Seasonal inundation, as the name implies, refers to a prevailing condition of surface water during the wet season for each year. During the succeeding dry period, the wetland may be dry or waterlogged.

Waterlogging, in the short term, is also likely to fluctuate seasonally with various degrees of sediment saturation. Wetlands with water tables in the upper 2 m interval are likely to experience waterlogging to various degrees, depending on sediment type and height of the zone of capillary rise. Brief intervals (days, weeks) after rainfall events wherein groundwater rises to intersect the wetland surface are incorporated into the regime of permanent and seasonal waterlogging. In the longer term, wetland waterlogging may be succeeded by drought conditions.

Permanent waterlogging is the new category of water regime in this paper. Here, inundation of the wetland would be a rare or uncommon rather than a prevailing condition. If a wetland is seasonally inundated, it may also be permanently waterlogged, however, the former presides over the latter state. Permanent waterlogging is likely to occur if the water table fluctuations are reduced and discharge rates are matched by continual recharge, *e.g.*, evaporation from the surface downward is countered by rising capillary and artesian pressure above the saturated zone.

Combining the types of landform and water regimes (or hydroperiod) results in various possible categories of wetlands (Table 3). Some categories axiomatically

Table 3

Matrix combining the land and water attributes and terms for wetland classes

	Water regime or hydroperiod				
	Permanent inundation	Seasonal inundation	Intermittent inundation	Permanent waterlogging	Seasonal waterlogging
Landform					
basin	LAKE[1]	SUMPLAND[2]	PIRAPI[4]	BASINMIRE[5]	DAMPLAND[2]
channel	RIVER[1]	CREEK[1]	WADI[1]	CHANNELMIRE	TROUGH[1]
vale				VALEMIRE[5]	PALUSVALE[5]
flat or plain		FLOODPLAIN[1]	BARLKARRA[4]	FLATMIRE[5]	PALUSPLAIN[2]
slope				SLOPEMIRE[5]	PALUSLOPE[3]
cliff				CLIFFMIRE[5]	PALUSCLIFF
hill-top				MONTMIRE[5]	PALUSMONT[3]

[1] existing term adapted for wetland terminology; [2] term coined by Semeniuk (1987); [3] term coined by Semeniuk & Semeniuk (1995); [4] terms adopted from the indigenous peoples of the Great Sandy Desert region for that type of wetland; pronounced "birabi" with the accent on the first syllable; [5] new terms coined in this paper

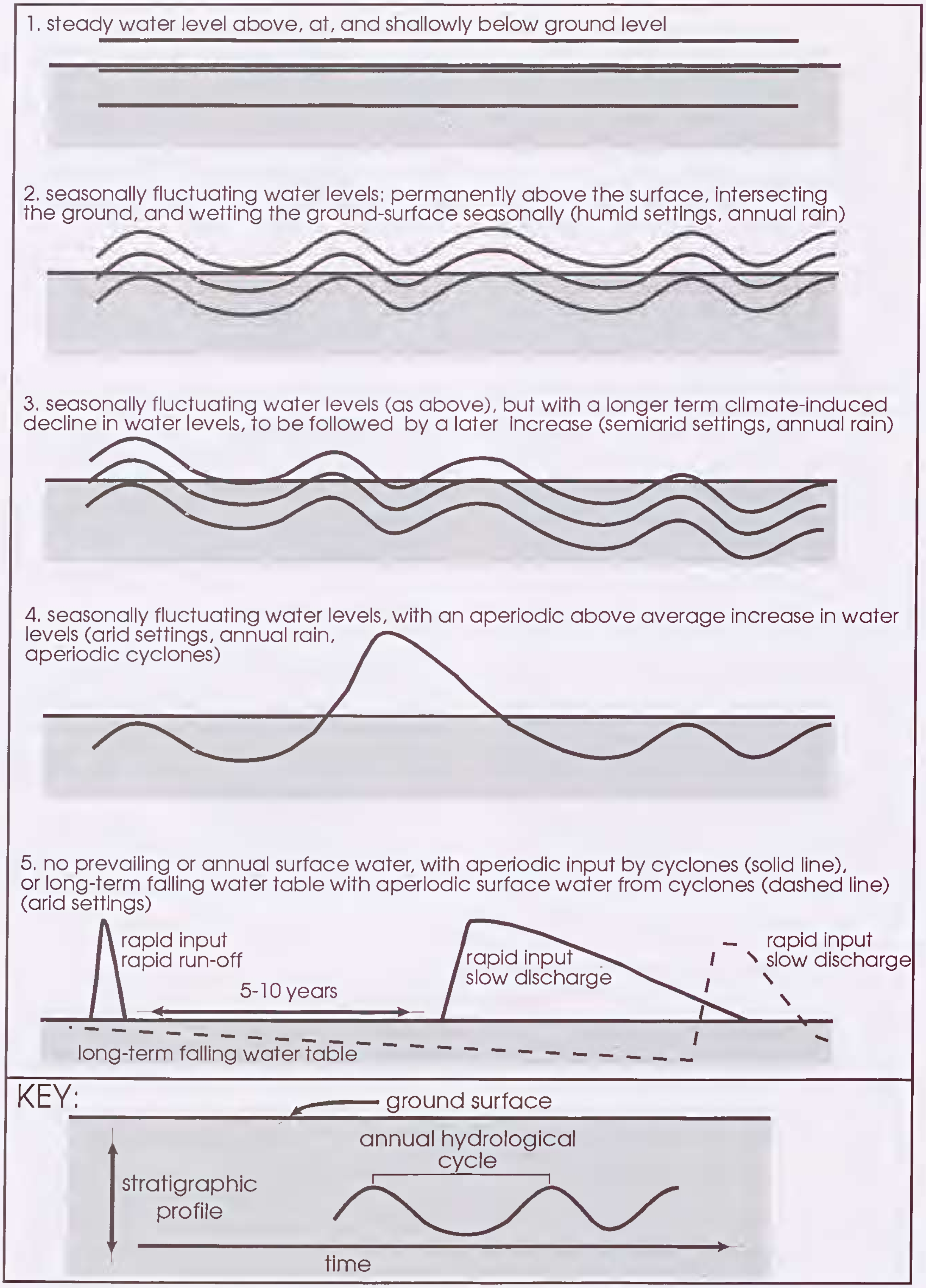

Figure 3. Typical graphs of wetland hydroperiods for surface and groundwater in a variety of hydrological settings.

are not possible (*e.g.*, permanently inundated hill-tops, or slopes), and so focusing on actual wet terrain that is realistic, there are 22 primary categories of wetlands, as follows:

Two criteria have been used to select terms for nomenclature: they must be single words, rather than multiples of words (*e.g.*, "seasonally inundated basin"), and preferably, if newly coined, the core attributes of the term should be deducible by its deconstruction (*e.g.*, palusmont, whose etymology is from Latin – *palus* and *mont*, meaning wet and marshy, and hill-top, respectively).

Existing terms have already been employed for some wetland categories (*e.g.*, lake, floodplain, river). The choice of "lake" and "river" was made because they have been used relatively consistently, in the literature and in common usage, to refer, respectively, to a permanently inundated basin and a permanently inundated channel. There has been some reluctance by scientists and wetland managers to accept these terms in their new context and constraints. Coleman (2003) expresses the view that: "Semeniuk (1987) ....creates the situation where a little brook in southern Australia is now a "river" and a major waterway in the northern area is now a creek". In practice, it is less likely to be a problem than is suggested, as waterways are not likely to be "major" very often if they are seasonal, and most creeks are likely to be small scale channels. Exceptions clearly exist, but adopting the variation in meaning results in a definition with greater precision as to landscape setting and hydrological regime. Importantly it avoids the use of a substitute term, if a new term is coined, which is likely to be even less familiar. However, we will further explore below the issues underlying these terms.

Our fundamental tenet that a wetland is a "land-and-water" feature of the Earth logically results in land and water being treated as primary attributes of the geomorphic-hydrologic classification. Primary attributes should be consistently applied within any classification. Thus, if a river is defined on attributes of landform (a channel-way) and hydrology (permanent inundation), the term "river" needs to be applied wherever a channel-way is permanently inundated, *regardless of scale*, and if a creek is defined on the attributes of landform and hydrology, the term "creek" needs to be applied wherever a channel-way is seasonally inundated, also regardless of scale.

To date, in Australia, there has been inconsistent use of terms for fluvial wetlands, often related to local usage. Large intermittently flowing waterways are variously named "river" or "creek", with the nomenclature appearing to be based on classification at a time when water was present, on size, and on historic precedent. The Gascoyne River, flowing only every 5 years (on average) is geographically termed a river. In this case it appears the term "river" is applied because it has the geomorphic form of a river, even though it does not have the hydrologic attributes of a traditional permanently flowing waterway. Similarly, many of the so-called "rivers" of the Pilbara region, regardless of their size, are surface-dry, sandy channel-ways for most of the year, and to attribute the term "river" to them, scientifically, misleadingly brackets them in the same hydrological context as permanently flowing waterways.

The choice of "floodplain" was made because *sensu stricto* its meaning is an inundated flat. The common association of the term "floodplain" with a channel is not incorporated in this context. New terms were coined by Semeniuk (1987) and Semeniuk & Semeniuk (1995) for "sumpland", "palusplain", "paluslope" and "palusmont" because existing terms such as "swamp", "fen", and "bog", carried with them meanings additional to land and water attributes (such as wetlands colonised by trees, or sustained minerotrophically, or underlain by peat) which often made the terms more parochial in application. Where terms have been coined for seasonally waterlogged terrains, the prefix "*palus*" has most often been used. New terms were coined where there were no pre-existing terms for a particular wetland type, *e.g.*, "dampland" for seasonally waterlogged basins and "barlkarra" for intermittently inundated flats (Table 3).

While previously Semeniuk & Semeniuk (1995) used the term "playa" to denote an intermittently flooded basin, its usage has since been re-considered in the light of its long term meaning in Australia, its variety of meaning across the world, and its etymology. The Spanish word, from which it has been appropriated, literally means "beach", but the term is now widely applied to dry lake beds or flats consisting of fine grained sediments infused with alkali salts (Neal & Motts 1967; Jankowski & Jacobson 1990, Briere 2000). In many other countries, there are local names for these features, *e.g.*, sabkha, takyr, kavir, alkali flats, and pan but, in each case, the term refers only to the attributes of dryness and/or saltiness. When rain filled, the depression is commonly termed a playa lake, which reverts to a playa when the water has evaporated.

The objective, in searching for a term for an intermittently flooded basin, was to emphasise the intermittent inundation of the land rather than water quality. In the classification presented in this paper, an intermittently inundated basin may be fresh water or saline, and underlain by mud or sand sized particles. We therefore propose replacement of "playa" of Semeniuk & Semeniuk (1995) with the term "pirapi", an indigenous word from the Karajarri language and people of the Great Sandy Desert region of Western Australia, referring to intermittently flooded basins that may be saline, brackish, or freshwater (Table 3). The indigenous peoples of the arid regions, in surviving in largely waterless desert environments for thousands of years, have categorised wetland environments for practical purposes, and commonly provide appropriate terms that encapsulate wetlands in terms of their permanence, intermittence, and maintenance.

For terms coined since 1987, we have attempted to have a consistency in nomenclature so that the landscape setting and hydrological regime of a wetland can be "unpacked" etymologically. Thus all permanently waterlogged wetlands end in the suffix "mire", and all seasonally waterlogged wetlands commence with the prefix "palus". The landform setting of the wetland also often is evident, *e.g.*, mont, slope, channel, and vale.

Although much peatland is permanently waterlogged, particularly in Europe, Russia and New Zealand, permanent waterlogging is also a common condition in many saline basins where the water table is near the surface underlying a salt crust. The suffix "mire", in its original meaning of "boggy, wet spongy earth", is resurrected here to be used in conjunction with a landscape type to denote the various types of permanently waterlogged terrains. It does not, in this context, denote water chemistry or water salinity, which may be acidic or alkaline, freshwater or saline. Neither, in spite of the tendency to associate "mire" with peat substrates (Gore 1983; Immirzi *et al.* 1992), does it imply the composition of the accumulated wetland sedimentary fill. Therefore it may be applied equally to any wetland whose surface sediments are aquatic, aeolian, alluvial, or sheet washed mineral and organic deposits that are permanently waterlogged.

Thus, embedded in single word terms are the attributes of landform shape and hydrologic regime, to which various descriptors can be added. For example:

- the term "lake" carries within the word the attributes of being a "basin that is permanently inundated",
- the term "basinmire" carries within the word the attributes of being a "basin that is permanently waterlogged", and
- the term "dampland" carries within the word the attributes of being a "basin that is seasonally waterlogged".

The wetland category of "springs" has not been included in this classification, although many authors and environmental managers make these wetlands a separate class because they are freshwater and important as drinking sources. "Spring" is used in the sense here of any groundwater discharge that reaches the surface, and includes permanent or seasonal flowing water, a seasonal trickle, and saturated sediments (Duguid *et al.* 2005). Springs within a basin or channel are not separated as a wetland type but viewed as a discharge mechanism contributing to the water regime. Springs, associated with slopes or mounds, that create a discrete wetland type, are named paluslope, slopemire, or mound spring. This approach mirrors in part that presented in the Ramsar Convention (Anon 1991, 1996) where springs are not categorised as wetland types.

Descriptors for non-emergent wetlands

For purposes of capturing wetland diversity, adding the adjectival descriptors will further separate types of wetlands, and it is at this level that attributes such as scale (size), hydrochemistry, wetland plant communities, and origin, can be emphasised.

Descriptors of landform

Scale is applied to individual wetlands, as a descriptor, using a fixed, defined frame of reference. For site specific wetlands, the scales of observation, or fixed frames, from Semeniuk (1987), are employed for wetland basins, slopes, and plains that tend to be equant in plan view and for wetland channels that tend to be linear (Fig. 4). Other landform attributes useful as descriptors for refining the wetland categories are shown in Figure 5. Application of landform descriptors is provided below, using a sumpland, with size, shape, and sediment as descriptors:

- mesocale sumpland
- mesocale, irregular sumpland
- mesocale, irregular, diatomaceous, sumpland

Descriptors of water

Hydrological attributes, useful as descriptors for refining various wetland categories, are: salinity, consistency of salinity, opacity and colour, specific hydrochemical characteristics, water source, water maintenance, depth, and rate of movement (Fig. 5). For instance, sumplands can be separated into four types on the basis of fresh or saline water descriptors alone:

- a freshwater stasosaline sumpland,
- a freshwater poikilohaline sumpland,
- a saline poikilohaline sumpland,
- a saline stasosaline sumpland.

Such categories will have follow-on implications for the type of biota resident in the wetland.

Descriptors of vegetation

A qualitative scheme for systematically classifying wetland vegetation was designed using the extent of vegetation cover and internal organization into plant communities (Semeniuk *et al.* 1990). The nine classes and their terms can be used as descriptors (Semeniuk *et al.* 1990). For further refinement, established structural and species dominance terms may be added.

Progressive use of descriptors

With progressive use of descriptors, various levels of wetland classification are possible, from simple high level classification (*e.g.*, as lake or sumpland), to more detailed and complex categorization, using a serial range of descriptors (Fig. 6). Reasons for categorization at the different levels range from mapping of wetlands at the regional scale (high level categorization) to comparative ecological or land assessments requiring characterization of their diversity at the local scale. An example of progressive classification is listed below:

- sumpland
- mesocale sumpland
- mesocale, subhaline sumpland
- mesocale, subhaline, diatomaceous sumpland
- mesocale, subhaline, diatomaceous, latiform, sedge covered sumpland

Self-emergent wetlands

As noted earlier, self-emergent wetlands are those that have accreted sedimentary, chemical and/or biogenic materials beyond their original geomorphic surface to develop a new wetland landscape. Progressive accumulation of autochthonous material in a basin, channel, flat, vale, or slope, may eventually result in the complete filling of the lowland and the development of a convex surface. Self-emergent wetlands should be differentiated from the accumulated *in situ* materials associated with convex wetland forms (hill tops and slopes), which conform to the underlying land surface, forming a geometric sheet or ribbon of wetland sedimentary products commensurate with the land contours. As the formation of self emergent wetlands is independent of the landform type which hosts these wetlands, they do not naturally lend themselves to the classification outlined earlier. In wetland mounds, the landform is not a fundamental component. However, such wetlands can still be categorised hydrologically.

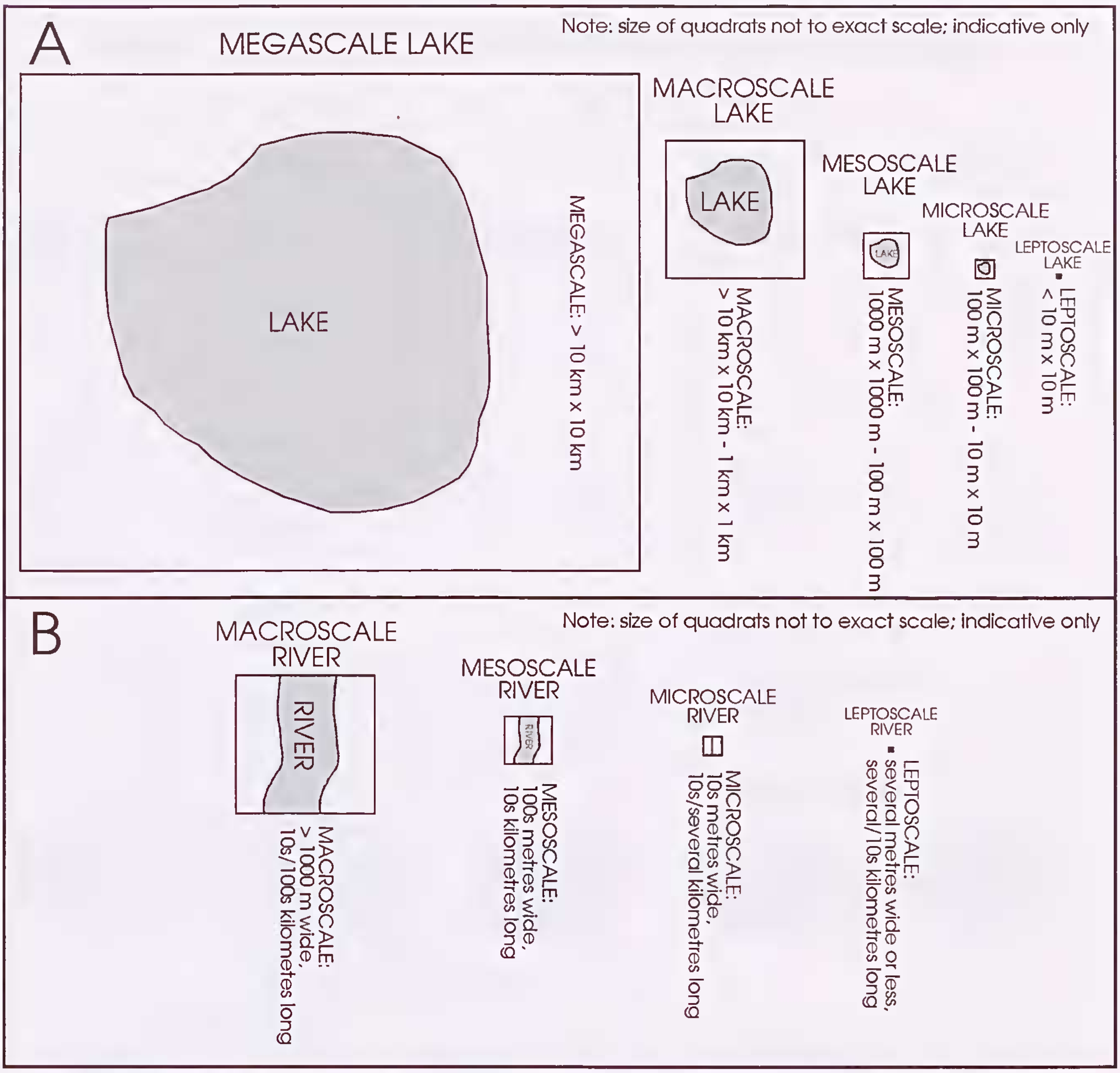

Figure 4. Scales of reference for equant and linear wetlands – plan view

Descriptors can also be applied to the various wetland mounds. For example self-emergent wetlands can be differentiated into several types, based on the composition of their accretionary material:

1 organic mound, or peat mound
2 phytolithic mound
3 diatomite mound
4 carbonate mound
5 gypsite mound
6 sinter mound
7 mud mound

Phytolithic lithology and diatomite tend to occur in layered structures, rather than as isolated homogeneous accumulations (*e.g.*, Belperio 1995; Ashley *et al.* 2002; Lynne 2007) In Western Australia, organic peat mounds occur, for instance, on the Swan Coastal Plain, at Eil Eil spring near Salt Creek (the Great Sandy Desert), at Mandora Soak, and along Geegully Creek (Gordon 2001; DEWHA 2010). Such mounds are permanently saturated, and water flows on the surface or from discrete channels. They are composed of peat, approximately 2–3 high, and some are surrounded by shallow moats. Peat and phytolithic mounds occur in a broad shallowly incised valley at Munro Springs with the permanently saturated central peat plug confined by carbonate mud under the lowlands and standing about 0.5 m above the surrounding plain.

Examples of carbonate mounds from several metres to tens of metres in diameter and up to several metres in height occur on the margins of the Great Artesian Basin, South Australia, where aquifers adjoin basement rocks, or where water escapes to the surface along fault lines and fracture zones (Boyd 1990; Mudd 2000; Harris 2002). Gypsite mounds are convex accumulations of gypsum. Examples occur in the "birridas" of Shark Bay region, and the saline basins of the Eyre Peninsula. They are formed

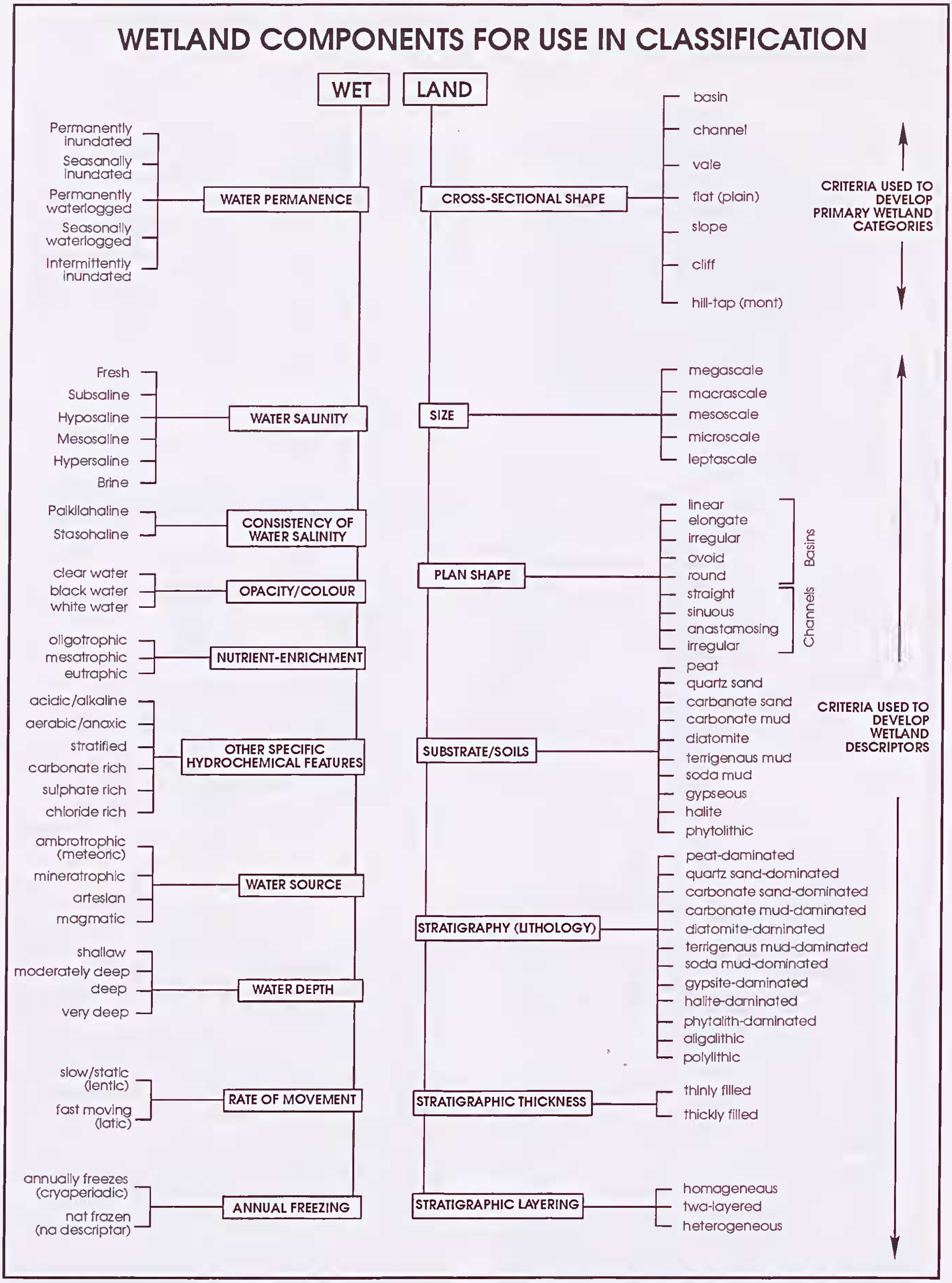

Figure 5. Range of land and water descriptors for the wetland classification. Sediment terms in part after Semeniuk & Semeniuk (2004)

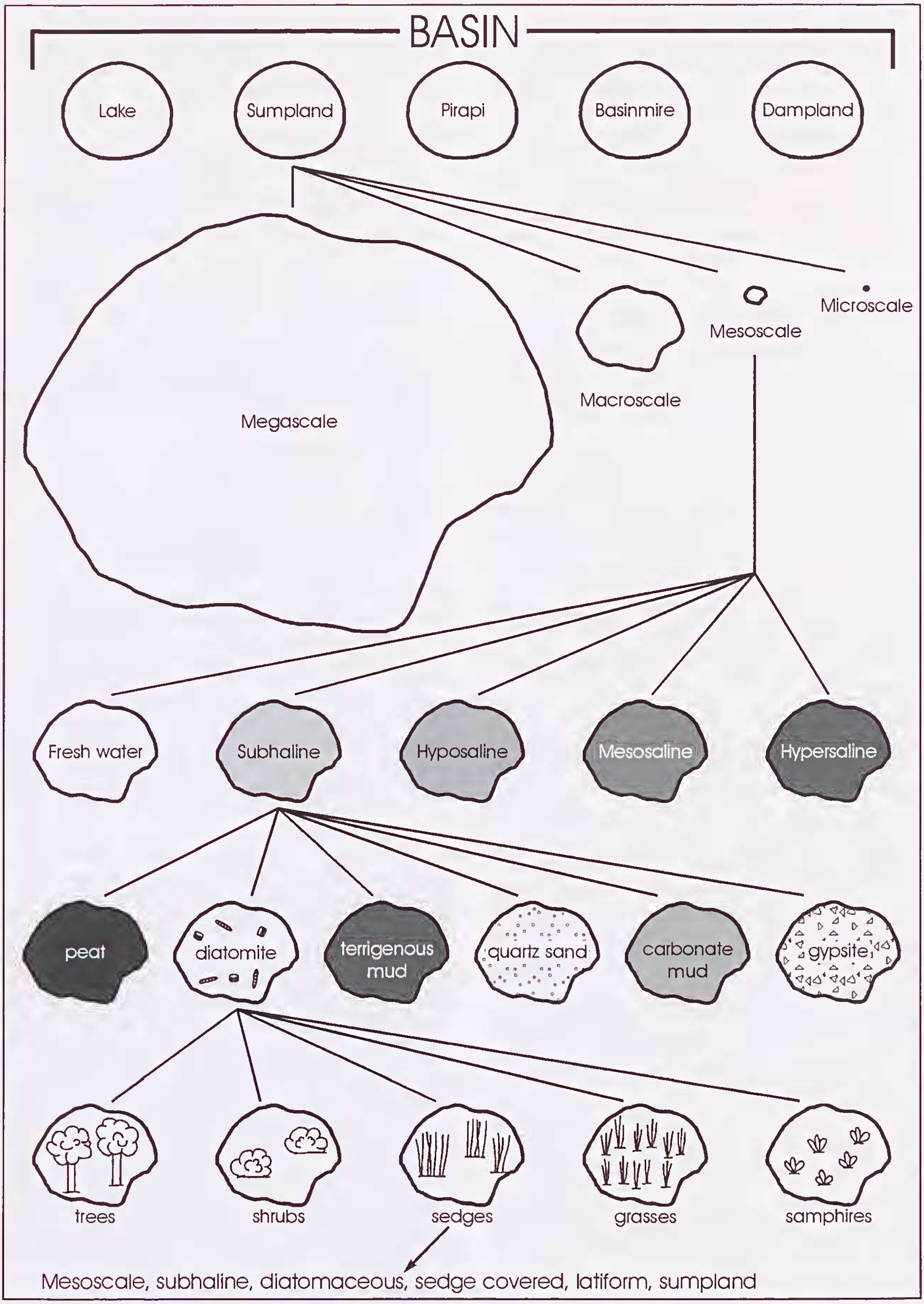

Figure 6. Use of a basin to illustrate levels of classification. Progressive levels of wetland discrimination use descriptors of scale, water salinity, wetland fill, and types of vegetation cover.

by gypsum precipitation from groundwater, causing crystal displacement, crystal accretion, and mounding of the surface. Siliceous sinter is a terrestrial hot spring deposit formed where silica-rich thermal fluids ascend to the surface and discharge in vents, pools, and outflow channels, usually in the region of volcanic activity (Inagaki *et al.* 2001; Lowe *et al.* 2001; Lynne 2007). Mud mounds are underlain by accumulations of clayey silt. Examples occur on the Liverpool Plains, and Gunnedah, New South Wales, where they overlie the Jurassic basalt. The permanently saturated mounds are flat topped, 1.2 m high and 4–8 m diameter, with ponds on the surface and intermittent flow (Acworth & Timms 2003).

Discussion and conclusions

In this discussion, the wetland geomorphic-hydrologic classification, saline wetlands, vegetation as a criterion for classifying wetland types, ecological character, and the use of the words classification and evaluation interchangeably, are explored.

Central to the geomorphic-hydrologic wetland classification is the tenet that land and water are the main determinants of wet lands and that the classification should reflect this. As a consequence, it follows that land and water features should be the primary criteria applied to every type or class of wetland. Several criticisms have arisen of this approach. Earlier in this paper, some discussion was presented regarding the ranking and importance of land and water attributes over scalar ones, and here this discussion is continued to include the use of scale to subdivide wetland types and the choice of terminology.

Stepping outside the current paradigm of usage of fluvial wetland terms, in this paper (and following Semeniuk 1987, Semeniuk & Semeniuk 1995), all permanently flowing channel-ways are classified as "rivers". Variation in size of rivers is denoted by a descriptor. Several critics of the wetland classification overlook the usefulness of appropriate adjectival descriptors. With a simple adjectival addition, a "brook" in South Australia can be classified in a straight forward way as a leptoscale river, a channel in southern Western Australia can be classified as a mesoscale river, and the Amazon River in South America as a megascale river – in all cases the term "river" denotes a permanently flowing waterway, a feature in common with each of the examples, and the scale descriptor denotes the size of the waterway. Similarly, a seasonally flowing channel-way in the Pilbara region is classified as a macroscale creek, which is hydrologically distinguishable by the nomenclature from a river.

Where channels vary in width from narrow to broader waterways, along their course, depending on the terrain they are traversing, the classification may be applied either to the whole system or to each segment. The Walpole River in Western Australia, for instance, is classified as a leptoscale river, but along its length, it varies in width from macroscale to leptoscale.

Thus, without the coining of new terms (for reasons outlined above), the terms "river" and "creek" (*sensu* Semeniuk 1987), with scale adjectival descriptors, firmly address wetland channel-ways that are permanently inundated *versus* those that are seasonally inundated.

Ponds, lakes and inland seas present another example where a wetland geomorphic-hydrologic type transcends scale but where a descriptor can be used to separate types of permanently inundated basins. Ponds and lakes are perceived as smaller and larger permanently inundated basins where scale is used as a *primary determinant* for classification and nomenclature (Cowardin *et al.* 1979). Although the rationale for this separation appears to be based on water depth and plant response, these size class distinctions have not been extended to other wetland types. Also there are permanently inundated wetland types that do not conform to Cowardin *et al.* 1979, being small but deep, or large but very shallow. If size categories were to be extended to other wetland types in the classifications adopting this approach, the number of wetland classes would increase significantly. We contend that landform (in this case, the basin itself) and hydrology (the permanency of inundation or waterlogging) should consistently be used as the primary determinants, and that small scale basins should be separated from larger scale basins by a descriptor.

The wetland classification, presented here, transgresses another widely held view about wetlands, in this case, "salt lakes". "Salt lakes" occur over 50% of Western Australia, and therefore constitute a significant proportion of the State's wetlands to be classified. As such, they merit some further discussion. The term "salt lake" has been applied to a variety of wet and dry habitats: samphire flats, bare areas, clay pans, sand basins, rock basins, lagoons, playas, playa lakes, and saline lakes (Bayley & Williams 1971; De Dekker 1983, 1988; Proctor 1990; Schubel & Lowe 1997; Yechieli & Wood 2002; Boggs *et al.* 2006; Lichvar *et al.* 2006; Gregory 2007; Shaw & Bryant 2011), although the arid zone contains few true lakes (perennially inundated basins), and those few invariably have inflowing rivers rising in fringing uplands, or distant humid areas (*e.g.*, the Caspian Sea, Dead Sea, Great Salt Lake and Lake Aral; Yechieli & Wood 2002; Timms 2006; Shaw & Bryant 2011).

The discussion on "salt lakes" that follows is focused on basins in order to be succinct. Arid zone basins owe their origin to the same broad spectrum of basin forming geomorphic processes as basins in humid zones, *viz.*, tectonic forces, meteor impacts, volcanic crater development, and biogenic, weathering, erosional, fluvial, depositional, and obstruction processes (Hutchinson 1957; Mabbutt 1977; Goudie & Wells 1995). Arid zone wet basins contain a variety of sedimentary deposits and geochemical environments (Mabbutt 1977; Goudie & Wells 1995; Reynolds *et al.* 2007; Shaw & Bryant 2011). Contrary to implications in the use of the term "salt lake" (and particularly the epithet "lake"), hydrological regimes for such designated bodies span conditions of permanent inundation, wet more than 75% of the time to dry more than 75% of the time with a negative water balance (Briere 2000, Timms 2006; Boggs *et al.* 2007; Castaneda & Garcia-Vera 2008; Shaw & Bryant 2011). The type of hydrological input to the basins may be 1. direct precipitation which becomes perched or infiltrates to recharge the water table, 2. inflowing groundwater 3. inflowing surface water, 4. saturation by a stable near surface water table, 5. inundation by a fluctuating near surface water table, or 6. combinations of the above.

Not all "salt lakes" contain salt. Evaporite mineral accumulation is dependent on the relationship between the position of the water table, and the role of groundwater in recharge, throughflow, or discharge, as illustrated in Rosen (1994) and Reynolds *et al.* (2007), and the type of evaporite mineral accumulation is dependent on salinity. Clay floored wetlands are characteristic of regimes with low groundwater input or where the surface lies above the influence of the zone of capillary rise (Neal 1969; Rosen 1994). Where the water table lies close to but does not intersect the basin floor, the groundwater salinity, density, and hydraulic conductivity of the aquifer, in combination with evaporative concentration, will determine the overall wetland salinity and usually results in salt precipitation (Bowler 1986), giving rise to the impression of ubiquitous "salt lakes" underlain by gypsum-dominated precipitates, or halite precipitates.

The aim of the present wetland classification for "salt lakes" is to separate out basins from flats, (ignoring at this primary level, their origin, sedimentary fill composition, and stratigraphy, position in the landscape, underlying geology, and scale), and to incorporate the hydrological regimes which are currently amalgamated under the term "salt lakes". In terms of water regime, "salt lakes" range from truly perennial shallow to deep water lakes to perennially dry basins (non-wetlands). In terms of the classification herein, "salt lakes" would be categorised as five different types of wetlands: saline lakes, saline sumplands, saline damplands, saline pirapis, saline basinmires, and one saline non-wetland basin – a playa. It is evident from this example that the diversity of wetland types, from a hydrologic perspective, is increased. The perched-freshwater wetland basins that occur amidst clusters of "salt lakes" in arid and semi-arid regions and are episodic, ephemeral, essentially closed systems, with fresh surface water that becomes brackish over time as evaporation decreases water volume and increases ionic concentrations, would be classified as freshwater poikilohaline pirapi. This designation potentially signals a wetland with different origin, different processes and functions.

It has been argued that in hierarchical wetland classifications, wetlands with very similar vegetation may be assigned to different classes on the basis of an attribute such as landform (Barson & Williams 1991). This perspective is underpinned by a practical consideration, that for most researchers, structural plant community types (heaths, grasslands, sedgelands, woodlands) and dominant species *within a region* are easily recognised, and can be used to identify wetland "types", while different substrates, hydrology, chemistry, and, even in some cases, landforms are not. There are three problems with this approach. Firstly, it suits regional projects rather than global ones. Secondly, it assumes that plant species and communities are surrogates for wetland hydrological regimes whereas, in reality, plant distributions are determined by numerous factors. Thirdly, it is underpinned by the notion that it is more important to link together wetlands with the same plant communities than it is to address the overall functioning of a wetland. Employing this perspective would result in superficial links between wetlands, particularly where there is a limited species pool. The corollary is that wetlands from different regions of the world would be separated from the main wetland groups, giving the incorrect impression that it is the wetlands that are diverse instead of the species pool being different. In Australia, this approach would result in permanently and seasonally inundated wetland basins, rivers, creeks, and floodplains all being classified as the same wetland type (*e.g.*, *Melaleuca* swamp) because they are all colonised by *Melaleuca rhaphiophylla*, or floodplains, creeks, wadis, palusplains, intermittently inundated basins, sumplands, estuarine flats and deltas, all being classified similarly because they are colonised by *Tecticornia halocnemoides*. The selection of more uniform and fundamental attributes could result in producing a platform on which global wetlands are comparable.

Another significant feature of the use of wetland classification relates to "ecological character" as defined in Resolution VII.10 of the Ramsar Convention. The values inherent in key environmental attributes determine a wetland's "ecological character". These key attributes include landform, substrate, scale and spatial arrangement, size, water regime, source and depth of water, salinity, and vegetation types and species. It is considered that if the wetland types distinguished in a classification do not have distinctive "ecological character", they will not be useful (Duguid *et al.* 2005). The following is a brief account of how the geomorphic-hydrologic classification, presented here, fulfils that objective.

Ecology is described as the study of relationships between organisms and their environment, including the study of communities, patterns of life, natural cycles, biogeography and population changes. The "relationship between organisms and their environment" is a complex one reaching back through a hierarchy of causes and effects from small to large scale. The landform host to the wetland is an important part of the wetland environment and determines many of the wetland functions that occur, such as the nature of sedimentary, hydrological and evolutionary processes. "Communities, relationships of organisms to each other, biogeography and population changes" directly respond to changes in landform size, landform aspect, height, structure, geometry, and setting. Landform also indirectly influences ecological response through its effects on water depth and water chemistry.

This can be expressed in myriad ways but a simple example is that of open *versus* closed systems. Below, the specific landforms selected for the wetland classification are listed in Table 4 beside corresponding sedimentary and hydrological wetland features and processes. Hydrochemistry would normally be included in Table 4 as a major link between landform and biota, however, it has not been included because it is so variable (for a given wetland it can include: neutral, acidic or alkaline rich waters and sediments, freshwater to hypersaline, waters that are iron rich, carbonate rich, dominated by sodium, calcium, potassium or magnesium, nitrogen rich, or phosphorous rich or poor, amongst others).

Table 4 shows that there are diverse processes operating in the various wetlands and that the number of these increase for the (relatively closed) basin wetland types. One of the most important controls that landform can exert on the ecological character of wetlands is water depth. Other features include closed *versus* open hydrological systems, *in situ versus* allochthonous sediment accumulation, and wetland fill composition,

Table 4

Range of attributes which commonly occur in each wet landform type

Landform type	Hydrological processes maintaining the wetland	Water regime, duration, depth of water	Sedimentological, pedogenic, diagenetic, or biogenic processes	Wetland fill or underlying wetland substrate
Hill top	1. Direct precipitation 2. Upwelling 3. Perching	Waterlogging Permanent or seasonal Shallow < 1 m	1. Weathering 2. Aeolian deposition	1. Soils 2. Saprolite 3. Blanket peat
Cliff	1. Runoff 2. Seepage	Waterlogging Permanent or seasonal Shallow < 1 m	1. Weathering 2. Biogenic accretion	1. Mineral deposits 2. Organic matter
Slope	1. Direct precipitation 2. Seepage 3. Surface flow	Waterlogging Permanent or seasonal Shallow < 1 m	1. Colluvial processes 2. *in situ* accumulation	1. Mineral deposits 2. Organic matter
Vale	1. Direct precipitation 2. Seepage 3. Groundwater	Waterlogging Permanent or seasonal Shallow < 1 m	1. Colluvial processes 2. *in situ* accumulation 3. Aeolian deposition	1. Organic matter 2. Quartz sand
Channel	1. Direct precipitation 2. Surface flow 3. Groundwater 4. Seepage	Inundation Permanent, seasonal, intermittent Waterlogging Permanent, seasonal Shallow < 1 m to deep	1. Fluvial erosion, transport, deposition 2. *in situ* accumulation	1. Clay, silt 2. Quartz sand 3. Gravel
Flat	1. Direct precipitation 2. Perching 3. Groundwater 4. Surface flow 5. Upwelling	Inundation Seasonal, intermittent Waterlogging Permanent, seasonal Shallow < 1 m	1. Fluvial deposition 2. *in situ* accumulation 3. Aeolian deposition 4. Diagenesis	1. Clay, silt 2. Quartz sand 3. Gravel
Basin	1. Direct precipitation 2. Springs or seepage 3. Groundwater 4. Perching 5. Discharge into basin 6. Sheet wash	Inundation Permanent, seasonal, intermittent Waterlogging Permanent, seasonal Shallow < 1 m to very deep > 100 m	1. *in situ* accumulation 2. Sheet wash 3. Aeolian deposition 4. Diagenesis 5. Biogenesis	1. Clay, silt 2. Quartz sand 3. Organic matter 4. Diatomite 5. Carbonate mud 6. Sponge spicules 7. Phytoliths 8. Gypsite 9. Evaporites

which vary between basins, flats, channels, slopes and vales. The water regime also is a prime determinant of ecological processes and interactions in the wetland. This is widely recognised and is important enough to be dealt with directly rather than through the use of plant species or plant community surrogates for hydrological conditions. The pattern of inundation, waterlogging, and drying, is a major influence on wetland biota populations and life cycles. Inundation and waterlogging are also strongly linked to, or influence water depth, water temperature, water salinity, and water chemistry, all of which have effects on community composition, distribution and viability.

Focusing upon landform and hydrology at the primary level of the classification sets the stage for further partitioning of wetlands based on attributes which affect biota at the scale of the individual wetland, individual sediment layer, water sediment interface, or rhizome layer. Variations in substrate or water chemistry in the subset of "sumplands" for instance, become more meaningful than a broad documentation of substrate across all types of wetlands.

As Figure 6 suggests, when the fundamental classification is augmented by just four descriptors, scale, salinity, substrate and vegetation, hundreds of different sumplands can be differentiated, which would underpin the different types of "ecological character".

From the recent literature, there appears to be a growing trend to perceive, and to use, classification as a tool, or a surrogate, for evaluation. The terms evaluation and classification are increasingly being used interchangeably (Brinson 1993, 1996, 2011; Millennium Ecosystem Assessment 2005). Classification, for purposes of discriminating wetland functions or utility, immediately brings into consideration value judgements of wetlands. In this paper, this approach is not followed because, in our experience, classification and evaluation have entirely different objectives and independent methods. The aim of classification is simply to group objects on the basis of common features, and one of its most practical applications is mapping.

This classification may be used to provide a world register and/or map of wetlands. From arid to humid climates wherever there are wet basins, hills, slopes, flats and channels, these can be categorised using landform and water regime attributes. Effort has gone into ensuring that the class terms are non-genetic and not dependent on local knowledge or on names of plant species. The terms are single words and many of them can be deconstructed into land and water descriptions. Finally, the number of classes which cover the global diversity of wetlands at the primary classification level is relatively small. It should be noted that at the primary level of classification this approach does not differentiate between a peat-filled basin that is permanently waterlogged by freshwater and a salt-encrusted basin that is permanently waterlogged by saline water. Both are classed as pirapi at the primary level. Their differences are brought out through the use of descriptors such as hydrochemistry, scale, stratigraphy, and biotic response.

As the classification scheme outlined above is based on landscape geometry and prevailing water regime, care is needed to assign categories where gradational boundaries exist between classes. Although most landforms can be easily assigned to one category or another, basins and slopes can grade into plains, and river channels can grade into lakes. This type of gradation is often linked to the stage of evolution of the landscape. In this context, both scale and setting are useful guides to choosing one or the other. The same situation can occur for water regime and hydroperiod and, here, the concept of prevailing conditions is useful. In a basin which is seasonally inundated for 7 out of 10 years, it is better for ecological purposes to focus on the prevailing condition rather than the exception and so this basin would be classified as a sumpland. Semeniuk & Semeniuk (1995) argue for simplifying the various categories of water regime into a few, so that classification becomes practical without reflecting every nuance of natural variation at the primary level, and this document continues this theme, presenting a simplified case of five water regimes. The objective of the classification is to provide broad classes of categories at the primary level, and use the descriptors to add details.

Wetlands may change over time and, in any classification, their dynamic nature may need to be addressed. Changes may occur in response to natural or anthropogenic influences. Natural climatic change, for instance, can determine both short and longer term responses of wetlands. These responses are effected through changes in hydrological and sedimentological patterns, hydrochemistry, and ecological and biological responses, and it is these which may be used to corroborate the classification in doubtful cases. Hydrological changes relating to water depth and wetland boundaries tend to be rapid and sometimes annual. Biological changes can be rapid and seasonal (aquatic invertebrates, rhizomatous plants) or slower and decadal (for established wetland species). Changes to wetland sediments tend to be in response to longer term changes in prevailing conditions. When it can be demonstrated that natural climatic change or anthropologic changes have altered the prevailing wetland hydroperiod in the longer term, as opposed to a short term fluctuation, then the classification of a given wetland will need to change.

Change due to anthropogenic causes is likely to be more rapid than those induced by natural climate change. The most important anthropogenic alterations are land clearing, water level perturbations (through water abstraction and drainage), and contamination. Each of these can radically alter the internal stasis and interactions that occur between soils, plants and water and, therefore, the type of wetland which results. A wetland classification should be such that these changes can be simply incorporated into the existing structure. This can transpire when the primary level of classification contains few but fundamental criteria.

Acknowledgements: This paper is part of VCSRG's R&D endeavour registered as Project # 3 with AusIndustry.

References

Acworth R I & Timms W A 2003) Hydrogeological investigation of mud-mound springs developed over a weathered basalt aquifer on the Liverpool Plains, New South Wales, Australia. Hydrogeology Journal 11: 659–672.

Anonymous 1991 Proceedings of the 4th Meeting of the Conference of Contracting Parties, Montreux, Switzerland. Published by Ramsar Convention Bureau, Gland, Switzerland.

Anonymous 1996 Ramsar Convention Bureau – definition and classification of wetlands. Articles 1.1 and 1.2. Gland, Switzerland.

Ashley G M, Goman M, Hover V C, Owen R B, Renaut R W & Muasya A M 2002) Artesian blister wetlands, a perennial water resource in the semi-arid rift valley of East Africa. Wetlands 22(4) 686–695.

Barson M M & Williams J E 1991) Wetland Inventory: towards a unified approach. Unpublished Report, Bureau of Rural Sciences.

Boggs D A, Boggs G S, Eliot I & Knott B 2006 Regional patterns of salt lake morphology in the lower Yarra Yarra drainage system of Western Australia. Journal of Arid Environments 64: 97–115.

Boggs D A, Eliot I & Knott B 2007 Salt lakes of the northern agricultural region, Western Australia. Hydrobiologia 576: 49–59.

Boulton A J & Brock M A 1999 Australian freshwater ecology: processes and management. Gleneagles Publishing, Glen Osmond.

Bowler J M 1986 Spatial variability and hydrological evolution of Australian lake basins: analogue for Pleistocene hydrological change and evaporite formation. Palaeogeography, Plaeoclimatology Palaeoecology 54: 21–41.

Briere P R 2000 Playa, playa lake, sabkha: proposed definition for old terms. Journal of Arid Environments 45(1): 1–7.

Brinson M M 1993 A hydrogeomorphic classification for wetlands. Wetland Research programme technical report WRP- DE-4 US Army Corps of Engineers MS, US.

Brinson M M 1996 Assessing wetland functions using HGM National Wetlands Newsletter 18: 10–16.

Brinson M M 2011 Classification of wetlands. In Le Page B A (ed) Wetlands Chapter 5 Springer.

Castaneda C & Herrero J 2005 The water regime of the Monegros playa –lakes as established from ground and satellite data. Journal of Hydrology 310: 95–110.

Coleman M 2003 Saline discharges into natural wetlands in Western Australia. Preliminary view of issues and options. Report to Department of Environmental Protection.

Cowardin L M, Carter V, Golet F C & La Roe E T 1979 Classification of wetlands and deepwater habitats of the United States. Fish and Wildlife Service US Department of the Interior Washington DC.

De Deckker P 1983 Australian salt lakes: their history, chemistry and biota – a review. Hydrobiologia 105: 231–244.

De Deckker P 1988 Biological and sedimentary facies of Australian salt lakes. Palaeogeography, Plaeoclimatology Palaeoecology 62: 237–270.

DEWHA (Department of Environment, Water, Heritage and the Arts) 2010 Assemblages of plants and invertebrate animals of tumulus (organic mound) springs of the Swan Coastal Plain. Threatened species and ecological communities.

Duguid A, Barnetson J, Clifford B, Pavey C, Albrecht D, Risler J & McNellie M 2005 Wetlands in the arid Northern Territory. Vol 1. A report to the Australian Government of Environment and Heritage on the inventory and significance of wetlands in the arid NT. Northern Territory Department of Natural Resources, Environment and the Arts, Alice Springs.

Fairbridge R W (ed) 1968 The Encyclopaedia of Geomorphology. Encyclopaedia of Earth Sciences Series Volume III. Dowden Hutchinson & Ross Inc., Pennsylvania, 618–626.

Gordon G 2001 Great Sandy Desert 1 McLarty subregion. A biodiversity audit of WA. Department of Conservation & Land Management, Perth.

Gore A J P (ed) 1983 Ecosystems of the world. Vols.4A and 4B Mires: swamp, bog, fen, and moor. Elsevier, Amsterdam.

Goudie A S & Wells G L 1995 The nature distribution and formation of pans in arid zones. Earth Science reviews 38: 1–69.

Gregory S J 2007 the classification of inland salt lakes in Western Australia. MSc thesis, Curtin University of Technology Western Australia.

Harris C R 2002 Culture and geography: South Australia's mound springs as trade and communication routes. Historic Environments 1–6.

Hettner A 1928 The surface features of the land: Problems and methods of geomorphology, (Translated by Tilley P 1972). Macmillan Press Ltd, London, xxi 14: 137–145.

Hutchinson G E 1957 A Treatise on Limnology. Vol. 1, Part 1. Geography and Physics of Lakes. John Wiley & Sons Inc., New York.

Immirzi C P & Maltby E 1992 The global status of peatlands and their role in carbon cycling. A report for Friends of the Earth by Wetland Ecosystems Research Group University of Exeter London.

Inagaki F, Motomura Y, Doi K, Taguchi Sizawa E, Lowe D R & Ogata S 2001 Silicified microbial community at Steep Cone Spring, Yellowstone National Park. Microbes and Environments 16(2): 125–130.

Jackson J A 1997 Glossary of geology (4th edition). American Geological Institute, Alexandria, Virginia.

Jankowski J & Jacobson G 1990 Hydrochemical processes in ground water discharge playas, Central Australia. Hydrological processes 4(1): 59–70.

Lichvar R, Brostoff W & Sprecher S 2006 Surficial features associated with ponded water on playas of the arid southwestern United States: indicators for delineating regulated areas under the Clean Water Act. Wetlands 26: 385–399.

Lowe D R, Anderson K S & Braunstein D 2001 The zonation and structuring of siliceous sinter around hot springs, Yellowstone National Park and the role of thermophilic bacteria in its deposition. *In:* Thermophiles: biodiversity, ecology and evolution (eds A L Reysenbach, M Voytek & R Mancinelli), Kluwer, 143–166.

Lynne B Y 2007 Diagenesis of siliceous sinter deposits in the USA and new Zealand. PhD thesis, Dept. of Geology, University of Auckland, New Zealand.

Lyons W B, Fountain A, Doran P, Priscus J C, Neumann K & Welch K A 2000 Importance of landscape position and legacy: the evolution of the lakes in Taylor Valley, Antarctica. Freshwater Biology 43: 355–367.

Mabbutt J A 1977 Desert Landforms. MIT Press, Cambridge USA.

Millennium Ecosystem Assessment 2005 Ecosystems and human wellbeing: wetlands and water. Synthesis World Resources Institute, Washington DC.

Mudd G M 2000 Mound springs of the Great Artesian Basin in South Australia: a case study from Olympic Dam. Environmental Geology 39(5): 463–476.

Neal J T 1969 Playa variation. *In:* Arid lands in Perspective (eds W G McGinnies & B J Goldman), University of Arizona Press, Tucson, 14–44.

Paijmans K, Galloway R W, Faith D P, Fleming P M, Haantjens H A, Heylingers P C, Kalma J D & Loffler E 1985 Aspects of Australian wetlands. Division of Land & Water Resources, Technical Paper 44, CSIRO, Melbourne, Australia.

Proctor V W 1990 Characeae of Llano Estado (Texas and adjacent New Mexico) playas. Journal of Biogeography 17: 75–84.

Reynolds R L, Yount J C, Reheis M, Goldstein H, Chavez P, Fulton R, Whitney J, Fuller C & Forester R M 2007 Dust emission from wet and dry playas in the Mojave Desert, USA. Earth Surface Processes & Landforms 32:1811–1827.

Richardson J L & Vepraskas M J (eds) 2001 Wetland Soils. Genesis, hydrology, landscapes, and Classification. Lewis Publishers.

Rosen M R 1994 The importance of groundwater in playas classification and the sedimentology and hydrology of playas. *In:* Palaeoclimate and Basin Evolution of Playa Systems (ed M R Rosen). Geological Society of America, Special Paper 289, USA, 1–18.

Schubel K A & Lowe T K 1997 Criteria for recognition of shallow perennial saline lake halites based on recent sediments from the Qaidam Basin, Western China. Journal of Sedimentary Research 67: 74–87.

Semeniuk C A 1987 Wetlands of the Darling System – a geomorphic approach to habitat classification. Journal of the Royal Society of Western Australia, 69(3):95–112.

Semeniuk C A 2007 The Becher Wetlands – A Ramsar site. Evolution of wetland habitats and vegetation associations on a Holocene coastal plain, south-western Australia. Springer, The Netherlands.

Semeniuk C A & Semeniuk V 1995 A geomorphic approach to global classification for inland wetlands. Vegetatio 118:103–124.

Semeniuk C A & Semeniuk V 2011 Review of classification of wetlands. Report to Ramsar Technical Committee STRP, Gland, Switzerland.

Semeniuk C A, Semeniuk V, Cresswell I D & Marchant N D 1990 Wetlands of the Darling System, southwestern Australia: a descriptive classification using vegetation pattern and form. Journal of the Royal Society of Western Australia 72: 109–121.

Semeniuk V & Semeniuk C A 1997 The geomorphic approach to global inland wetland classification and rationalisation of the system used by the Ramsar Bureau – a discussion. Wetland Ecology & Management 5: 145–158.

Semeniuk V & Semeniuk C A 2004 Sedimentary fill of basin wetlands, central Swan Coastal Plain, southwestern Australia. Part I: sediment particles, typical sediments, and classification of depositional systems. Journal of the Royal Society of Western Australia 87: 139–186.

Shaw P A & Bryant R G 2011 Pans, playas and salt lakes. *In:* Arid zone geomorphology: process, form and change in drylands (3rd Edition) (ed. D S G Thomas). John Wiley & Sons Ltd, Ch 15.

Timms B V 2006 The geomorphology and hydrology of saline lakes of the Middle Paroo, arid-zone Australia. Proceedings of the Linnean Society of New South Wales 127: 157–174.

Tiner R W 1999 Wetland indicators. A guide to wetland identification, delineation, classification, and mapping. CRC Press.

von Engeln O D 1949 Geomorphology systematic and regional. McMillan Co., New York, 1–74.

Warner B G 2004 Geology of Canadian wetlands. Geoscience Canada 31(2): 57–68.

Yechieli Y & Wood W W 2002 Hydrogeologic processes in saline systems: playas, sabkhas, and saline lakes. Earth Science Reviews 58: 343–365.